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A turbulent MHD model for molecular clouds and a new method of accretion on to star-forming cores

D. Balsara[1], D. Ward-Thompson[2], R. M. Crutcher[1,3]
[1] *NCSA, University of Ilinois, Champaign-Urbana, Illinois, USA*
[2] *Dept of Physics and Astronomy, Cardiff University, PO Box 913, Cardiff CF2 3YB*
[3] *Dept of Astronomy, University of Ilinois, Champaign-Urbana, Illinois, USA*

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ABSTRACT
We describe the results of a sequence of simulations of gravitational collapse in a turbulent magnetized region. The parameters are chosen to be representative of molecular cloud material. We find that several protostellar cores and filamentary structures of higher than average density form. The filaments inter-connect the high density cores. Furthermore, the magnetic field strengths are found to correlate positively with the density, in agreement with recent observations. We make synthetic channel maps of the simulations and show that material accreting onto the cores is channelled along the magnetized filamentary structures. This is compared with recent observations of S106, and shown to be consistent with these data. We postulate that this mechanism of accretion along filaments may provide a means for molecular cloud cores to grow to the point where they become gravitationally unstable and collapse to form stars.

Key words: stars: formation

1 INTRODUCTION

Surveys of the densest cores of molecular clouds (eg: Benson & Myers 1989; Ward-Thompson et al. 1994) have shown them to be sites of active star formation, which can collapse under self-gravity to form objects known as protostars. A protostar is an object which will evolve into a star, but which is currently in the process of accreting the major part of its final main sequence mass (eg: André, Ward-Thompson & Barsony 1993 ; Shu et al 1993). The nature of this accretion process is still a matter of debate, although it is known that for low-mass stars ($M \leq 4$–$5\ M_{\odot}$) the protostar finally emerges from its enveloping cloud of material onto a well-defined pre-main sequence track on the H-R diagram (Stahler, Shu & Taam 1980), and hence to the main sequence.

Much current debate centres around how dense cores in molecular clouds form initially, and how they subsequently evolve. One school of thought suggests that cores form by Jeans-type gravitational instabilities (eg: Blitz & Williams 1997), and subsequently evolve to higher densities by means of ambipolar diffusion (eg: Ciolek & Mouschovias 1994). This is a process whereby a large-scale magnetic field threading the dense core supports the ionised component of the material against collapse while the neutral gas diffuses under self-gravity towards the centre of mass. This causes the centre of the core to increase in density until a critical mass-to-flux ratio is reached, and runaway gravitational collapse sets in.

However, there is a growing body of observational evidence that these quasi-static equilibrium processes are not the only important physical processes in the evolution of the interstellar medium. Excess emission at higher velocities than purely thermal emission (e.g. Falgarone & Phillips 1990) have been explained in terms of intermittent velocity behaviour, which is a characteristic of turbulence. It has also been shown that the linewidths of molecular gas emission can be decomposed into a thermal and a non-thermal component (e.g. Casselli & Myers 1995), where the non-thermal component is produced by turbulence. Likewise, it has been seen (Crutcher 1999) that there is a strong tendency for molecular cloud material to have velocities that are supersonic and mildly sub-Alfvenic. Therefore, any complete understanding of the physics of the interstellar medium should include consideration of a self-gravitating magnetohydrodynamic (MHD) fluid undergoing turbulence.

There have been a number of MHD models that have recently been published. For example, Gammie & Ostriker (1996) showed that MHD turbulence can inhibit gravitational collapse. However, that model was limited to a slab geometry for molecular clouds. Subsequently, Ostriker, Gammie & Stone (1999) presented the results of a 2.5-D MHD simulation, and showed that the ratio of magnetic to thermal pressures in a molecular cloud provides an indicator as to how the cloud will evolve to form stars. A number of authors have shown that turbulence tends to decay on relatively short time-scales compared to the life-times of molec-

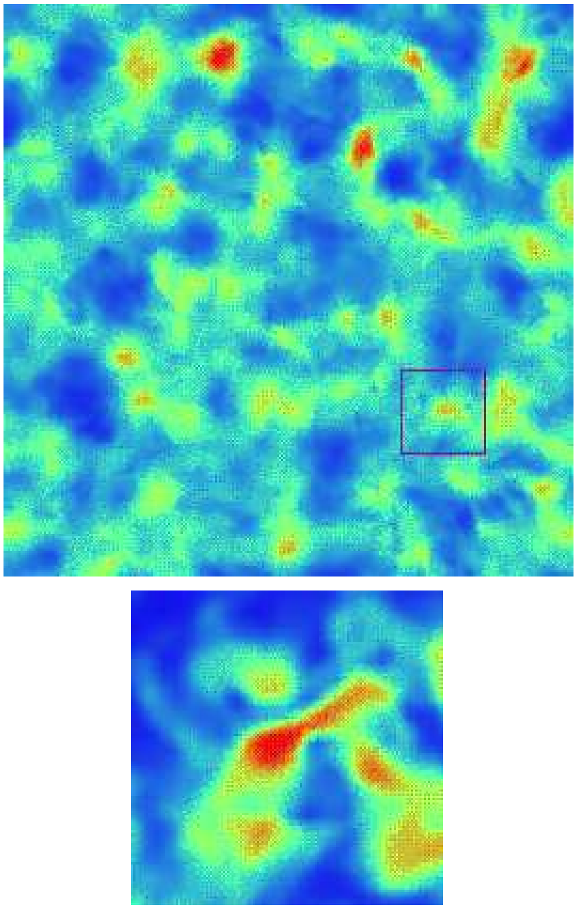

Figure 1. Panel (a) (upper) shows the simulated total intensity, assuming optically thin emission, from the model cube once pronounced cores have formed. The red outline identifies the core magnified in Figure 1(b). Panel (b) (lower) shows the integrated intensity from the core delineated in Figure 1(a). Velocity channel maps for this core are shown in Figure 3.

ular clouds (e.g. Stone et al., 1998; MacLow 1999). However, there are many potential driving mechanisms of turbulence that could counteract this decay, such as stellar winds, jets and outflows, as well as large-scale motions such as shearing caused by Galactic differential rotation. In this paper we present the results of fully three-dimensional simulations of turbulent MHD flows in molecular clouds and compare them with observations.

2 THE MODEL

A three dimensional cubic computational domain with 256^3 zones that is initially 2 pc across was set up with a density of 10^{-20} g cm^{-3}. A tapered exponential spectrum of velocity and magnetic fluctuations was initially used (see Balsara & Pouquet 1999; Balsara, Crutcher & Pouquet 1996; Balsara, Crutcher & Pouquet 1999). The initial conditions consisted of flow that had a turbulent root-mean square (rms) Mach number of 1.5 and an Alfven Mach number of unity. These initial conditions are consistent with the observations of several molecular clouds, particularly those 'starless' clouds in which star formation has not yet begun (e.g. Crutcher 1999; Benson & Myers 1989 and references therein). Periodic boundary conditions were utilized. The initial conditions are very similar to the unforced models described in Balsara & Pouquet (1999) with the only difference that the simulation presented here is self-gravitating.

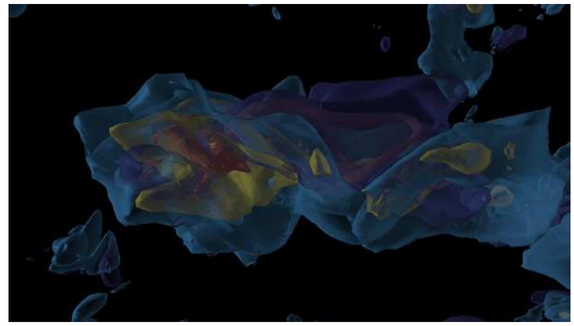

Figure 2. Isosurfaces of density and magnetic field magnitude superposed. Cyan, yellow and red indicate isosurfaces of density that are four, six and eight times the mean density. Purple and magenta indicate isosurfaces of the magnitude of the magnetic field that are five and seven times the mean. Note the spatial coincidence of density and magnetic field strength.

This simulation is one of several isothermal and mildly adiabatic (adiabatic index of 1.2) simulations that we have carried out over a range of realistic turbulent rms Mach numbers and Alfven Mach numbers. Truelove et al. (1997) found that isothermal collapse can form gravitationally condensed structures on all scales, which is unphysical, but that an adiabatic equation of state can arrest collapse on certain scales. A compromise to this issue was suggested by Boss et al. (2000), who advocated using a barotropic equation of state. We intend to explore this solution in subsequent papers, but we note that the compromise between adiabatic and isothermal equations of state that we present herein appears to overcome the problems noted by Truelove et al. (1997).

The simulation was carried out on a fixed grid, and it is well documented that the grid-based criterion needs to be satisfied for the condensed objects (cores) in order for their inner structure to be properly analyzed (e.g. Truelove et al. 1997). Satisfying the grid-based Jeans criterion is not always possible on all scales. However, our focus in this paper is not on the inner detailed structure of the cores, rather it is on the accretion that takes place on to the cores. For those length-scales our conclusions are unaffected by the grid-based Jeans criterion. We evolved the model using the RIEMANN code for numerical MHD (Roe & Balsara 1996; Balsara 1998a&b; Balsara & Spicer 1999a&b).

2.1 Results of the simulations

Figure 1(a) shows the simulated total intensity, assuming optically thin emission, from the model cube after a few crossing times. It can be seen that the model molecular cloud has some regions of lower than average density, as well as compact regions of much higher density. Furthermore, the regions of highest density appear to be connected to one another by linear features. Examination of the whole model

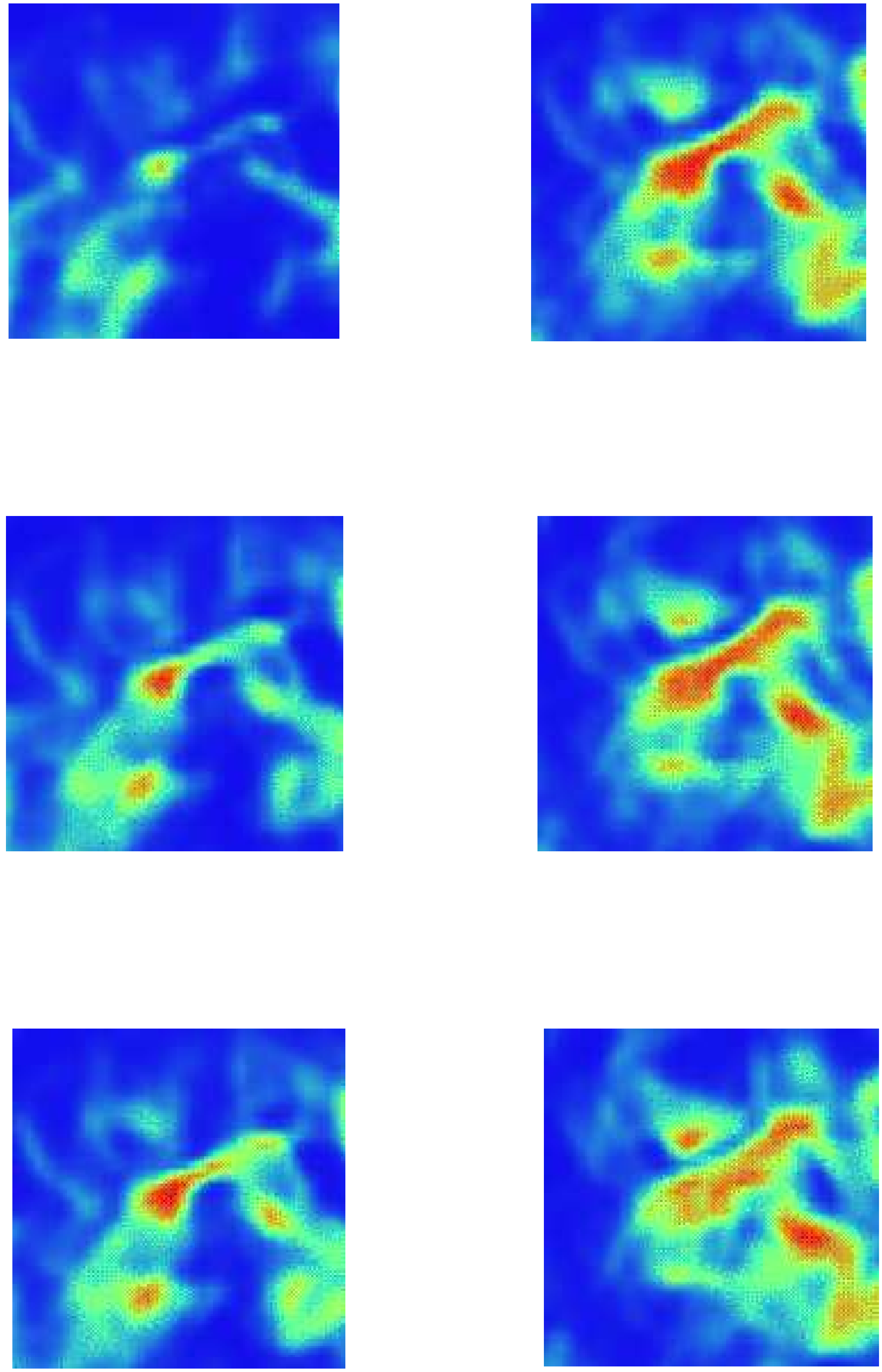

Figure 3. Panels (a)–(c) (left-hand column) and (d)–(f) (right-hand column) show simulated channel maps of the same dense core shown in Figure 1(b) and its surrounding filamentary structure. Each panel represents a single velocity slice through the region. The ratios of the line of sight velocity to the thermal width are −1.04, −0.80, −0.66, −0.41, −0.27 and −0.07 respectively.

cube reveals that these linear features are essentially one-dimensional filaments, rather than two-dimensional sheets seen 'edge-on'. All of the filaments terminate in at least one high density region, while many of the filaments link two high density regions. The filaments arise as a result of converging gas flows in a turbulent medium.

We also see in our simulations that matter accretes on to the cores along the filaments. The high density cores are all compact, and have diameters ranging from a few hundredths of a parsec to little over a tenth of a parsec. The larger cores are reasonably well-resolved, occupying over twenty zones. However, all of the cores satisfy the numerical resolution criterion (e.g. Truelove et al. 1997). The densities of the cores are high, having typical values of $n(H_2) \geq 6\times10^4 cm^{-3}$. These sizes and densities are consistent with those observed in dense cores in actual molecular clouds (e.g. Benson & Myers 1989).

We have analyzed the correlation between the magnetic field strength and the density in such simulations (Balsara et al. 1999) where we showed that statistically there is a very strong positive correlation. In Figure 2 we show the correlation visually using iso-surfaces of density and magnetic field magnitude superposed on the same image of an isolated core. Thus cyan, yellow and red indicate iso-surfaces of density that are four, six and eight times the mean density. Purple and magenta indicate iso-surfaces of the magnitude of the magnetic field that are five and seven times the mean. We see that both the density and magnetic field correlate positively and also that they are stretched out in elongated filamentary structures. Furthermore, the magnetic field direction typically lies along the cores, where it could serve to 'funnel' gas onto cores (see below).

Quantitative analysis shows that several of the cores are magnetically supercritical, in agreement with the observational findings (Crutcher 1999). The model has, therefore, illustrated the topological structures of density and magnetic field in turbulent magnetized molecular clouds and cores.

2.2 Accretion onto cores

Figure 3 shows simulated channel maps of one of the dense cores and its surrounding filamentary structures. The channel maps were made assuming optically thin emission. The region of Figure 1(a) that we have magnified in Figure 3 is shown by the red outline in Figure 1(a) and is also shown in close-up in Figure 1(b). The channel maps were obtained by convolving the line of sight velocity with the thermal broadening. Analysis of the channel maps shows that the magnified region consists of two cores that are very well separated in velocity space. We focus on one of them here.

Figure 1(b) shows the integrated intensity of the selected core. Each of the panels of Figure 3 represents a single velocity slice through the region. The caption gives the ratio of the line of sight velocity to the thermal width. The range of those numbers clearly shows that the motions are indeed supersonic. Figure 3(c) corresponds to the core's rest velocity. From Figure 1(b) we notice that there is one filament heading in a north-easterly direction from the core.

In most situations it is reasonable to expect that matter will accelerate along one part of a filament and also decelerate along another part. Gravity should cause the mass to accelerate towards a core, while certain magnetic field topologies, as well as the presence of shocks or density gradients in the accreting material, would cause matter to decelerate as it approaches a core. The simulated channel maps allow us to dissect the acceleration or decelaration of mass as it flows along the filaments. In general the filaments can be curved, but a simple model that assumes linear filaments that make contact with a core at one of their ends allows us to draw some simple deductions on how to interpret channel maps.

Figure 4(a) shows a schematic diagram of a core that has two filaments with accreting matter that is decelerating towards the core. A little reflection shows that, if there is pure deceleration of accreting matter that is flowing in a linear filament towards the core, the local maximum in the emission intensity should appear to move away from the core as one steps away (in velocity space) from the core's rest velocity. This is schematically illustrated in Figure 4(b), where we show the motion of the intensity maxima in the channel maps. Pure accceleration of matter in a linear filament should show the opposite trend in the channel maps. It should also be pointed out that constant velocity flow along a curved filament can also appear to be an acceleration or a deceleration depending on the filament's orientation relative to the observer.

The schematic diagrams in Figure 4 allow one to interpret the simulated channel maps in Figure 3. Figure 3(a) shows only the core with a very faint suggestion of filamentary structure. Figures 3(a)–(f), viewed in sequence, show the intensity in the filament become progressively stronger as the core itself becomes fainter. In Figure 3(e) the core is decidedly fainter than the filament and in Figure 3(f) it is very much fainter than the filament. By viewing Figures 3(a) through to 3(f) in sequence one also notices that the intensity maximum in the filament moves away from the core in a north-westerly direction traced out by the filament in the total intensity map of Figure 1(b). In view of the discussion above, we interpret this as deceleration of matter along the filament in the simulated channel maps in Figure 3.

From the range of velocities quoted in Figure 3 we notice that the velocity ranges over an entire Mach number in this case. We have carried out such imaging for numerous cores in the simulation presented here as well as in numerous other simulations that we have carried out. While a filamentary structure that is aligned along the line of sight will not stand out prominently, we found that most cores have filamentary structures around them. Larger cores show more filamentary structures, a fact that finds a natural explanation in this scenario, as will be shown below. The velocities that develop along these filaments correspond to a range of one or more Mach numbers.

What we appear to be observing in Figure 3 is material decelerating along a filament towards a dense core. Remember that the densest regions in the simulated molecular cloud are also the regions of highest magnetic flux density. Thus the filaments, as well as being regions of higher density, are also regions of higher magnetic flux density. Figure 2, as well as our earlier results (see Balsara et al. 1998) have shown us that the magnetic field lines tend to lie along the filaments.

Hence these filaments are effectively magnetic flux tubes in the molecular cloud, which are linked to the dense cloud cores. So we interpret Figure 3 as illustrating how material can be channelled by magnetic flux tubes and flow onto the dense cores. Thus the model simulation has indicated one

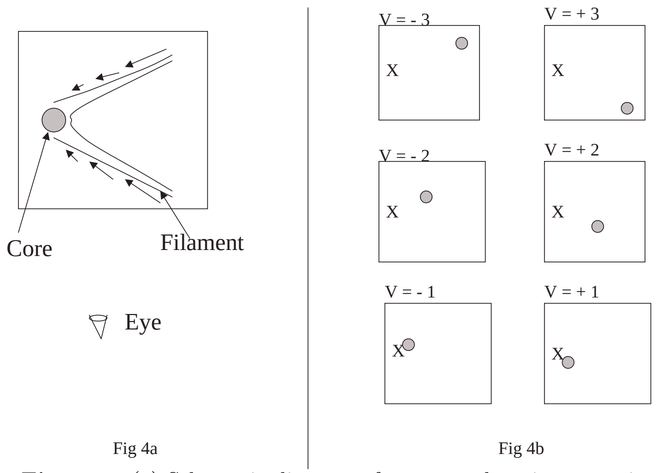

Figure 4. (a) Schematic diagram of a core undergoing accretion along filaments. The shaded area denotes the core. The two linear structures correspond to two filaments. The arrows along the filaments denote velocity vectors. The rest velocity of the core is taken to be zero. The image of the physical system is shown in plan view. To break the degeneracy of having the two filaments appear in the same line we ask the reader to tip the edge of the figure that is farther from the eye a little above the plane of the paper. (b) Schematic diagram of the channel maps that would be produced by the situation in (a). The 'X' in the channel maps shows the core's location. The shaded blob shows the location of the intensity maximum at that scaled velocity (which is shown immediately above each channel map).

method in which dense cores may evolve and grow in mass by accretion along magnetic flux tubes. We also document that this process is seen to occur very often for other cores that form in several of our simulations.

This suggests that the amount of mass built up by a core over time will depend strongly on the topological structure of the magnetic fields that link to that core. The fact that larger cores seem to have more filaments is now consistently explained by the fact that larger cores are connected to more magnetic flux tubes which, therefore, supply them with accreting matter at a faster rate. Our new paradigm for core formation seems to form a substantial number of magnetically supercritical cores. While consistent with recent observations (e.g. Crutcher 1999) this fact is at variance with a previous paradigm for core formation (Mouschovias and Spitzer 1976) which suggests that cores that form are initially magnetically subcritical and only a portion of the core becomes supercritical through the workings of ambipolar diffusion.

The difference in the two paradigms stems from the fact that matter is accreted directly along field lines in these dynamical models while the previous models thought of core formation as taking place through a sequence of quasi-steady states. In other work (Balsara, Crutcher and Pouquet 1999) we showed that ambipolar diffusion does not play a significant role in damping out the turbulence because the nonlinear eddy turnover times are shorter than the ambipolar diffusion time. Hence the inclusion or exclusion of ambipolar diffusion does not strongly affect these results. In the next section we compare the model findings with one particular molecular cloud region, to discover whether the predictions of the model may actually occur in reality.

3 COMPARISON WITH S106

In Figure 5 we show ^{13}CO channel maps of the S106 molecular cloud. The black contours trace the 800-μm dust continuum emission and, therefore, serve to identify the location of the protostellar core. The numbers at the corner of the figures show the velocity in kms^{-1} for each of the channel maps. Figure 5(d) corresponds to the core's rest velocity. Based on temperature measurements of S106 the thermal sound speed can be estimated to be 0.5 kms^{-1}

S106 contains at its eastern edge S106-IR, and at its western edge the core which was identified from its submillimeter dust emission as S106-FIR (Richer et al. 1993). The latter source has no known outflow or associated protostar, and so is a candidate core for comparison with our model. There are two filaments which join this core from the north-east that can be seen partly over-lapping in Figure 5. There is also a much smaller filamentary structure that joins it from the south-east. The two north-eastern filaments overlap each other to a great extent in the total intensity maps but can be separated from each other in the channel maps. The temperature in the filamentary gas has been measured and is too low to permit one to interpret the filaments as outflowing gas.

The channel maps in Figure 5 of the velocity structure taken with the BIMA interferometer show evidence for velocity deceleration in the gas that is accreting along the length of the filaments if one assumes that the filaments are not curved along the line of sight (Roberts & Crutcher 2001). However, one of the filaments in S106 appears to be curved in the plane of the sky, making it difficult to deduce whether we are seeing acceleration or deceleration along it. In any case, the existence of filamentary structures and the motion of the intensity maxima along the filaments as one steps through the channel maps in Figure 5 shows that these data are in close agreement with the model predictions shown in Figure 3. Thus we conclude that the accretion process in this core of S106 is taking place preferentially along the filaments.

Polarimetric observations (Hildebrand et al 1995; Holland et al 1996) suggest that the magnetic field is also preferentially aligned along the long axis of the filaments, a fact that is also consistent with the simulations. Thus the data for this cloud suggest a scenario where the magnetic fields serve to channel the accreting material along the filaments, and the data are consistent with our hypothesised model scenario. If this hypothesis is proved by further observations, then we have shown how cores grow to become super-critical, and hence collapse to form stars.

4 CONCLUSIONS

Using simulated channel maps from a numerical MHD simulation in conjunction with observational data of S106, we have been able to arrive at several insights into the process of accretion onto the molecular cloud cores in which stars form:

(i) Turbulent MHD processes cause the formation of high density cores;

(ii) The cores are linked by extended filamentary structures;

(iii) Several of the simulated cores are found to be magnetically supercritical;

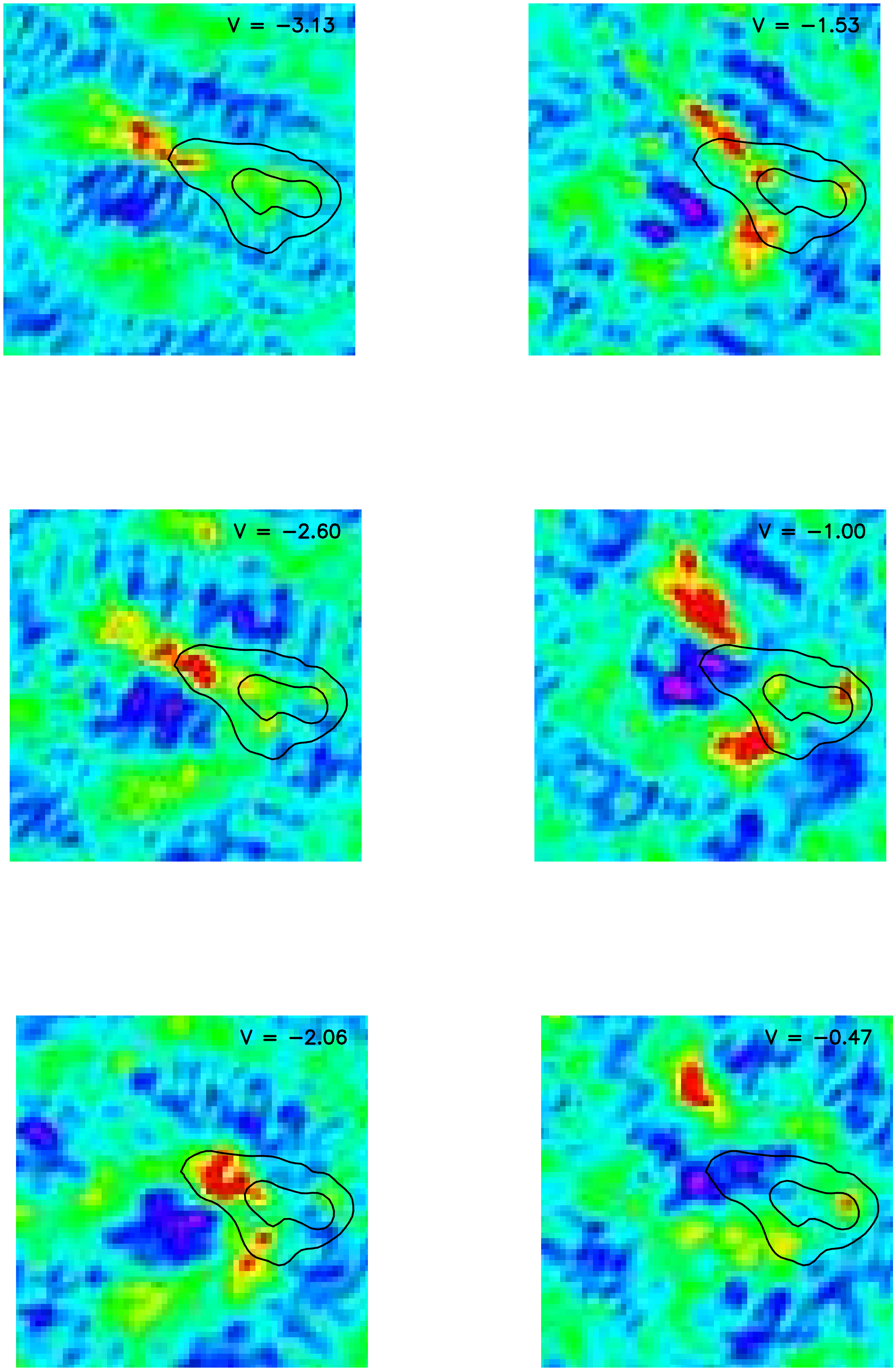

Figure 5. ^{13}CO channel maps of the S106 molecular cloud. The black contours trace the 800-μm dust continuum emission and therefore serve to identify the location of the protostellar core. The numbers at the corners of the figures show the velocity in kms^{-1}.

(iv) The higher density filaments are aligned with the magnetic field structure;

(v) The accretion onto the cores takes place along the filaments;

(vi) This suggests a scenario where the material is channelled by the magnetic field and flows under the gravitational influence of the dense cores at the ends of the filaments, accreting onto the cores themselves;

(vii) The amount of matter accreting on to a core thus depends on the topological structure of the magnetic fields that link to that core;

(viii) Our observations of S106 appear to show this process occurring in a real molecular cloud.

If observations of other regions show similar results, then this would show that we have distinguished for the first time an important way in which star-forming cores accrete matter to the point where they have gained sufficient mass to undergo dynamical collapse and form stars.

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